Investigation on Coherent Scatterers in Natural Environment for SAR Multi-Image Applications

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Chapter 6

Summary and Outlook

The aim of this thesis was to provide phase stable scatterers in forest environment when the number of available SAR images is limited, and we have focused on the CS technique and have improved for this aim.

One of the great advantages of the CS technique is that the technique enables the detection of scatterers with high SCR from single SAR image. The CS technique evaluates the sublook coherence (SLC) which is the correlation coefficient between two sublook spectrums extracted from full image spectrum. The scatterer with high SLC is associated as CS.

The dihedral structures composed of the tree trunks and the ground which induce the double-bounce scattering are considered to possess the potential to be CSs in forest environment. Different from man-made objects, the direction of sublooks formation would not be the problem since such cylinder-like-structure over the ground does not show a strong azimuth aspect angle dependency on the reflectivity. The resolution, which is proportional to the bandwidth, is finer in azimuth than in range as in most SAR systems, therefore the CS detection based on the azimuth SLC rather than the range one was adopted for forested area applications.

In Chapter 4, experimental results have been demonstrated with P-band Pol-InSAR datasets acquired in repeat-pass InSAR mode over boreal forest test site by DLR's E-SAR airborne system in order to show the potential of CSs as being phase stable scatterers. The number of tracks was 6 and the largest temporal baseline was 2 hours. We could see that high SCR derived from the SLC is related to high ensemble coherence, namely high SLC is related to high phase stability. CSs were shown to be phase stable scatterer as PSs.

The detection results of CSs and PSs were compared too. CSs were distributed relatively evenly without range dependency. Especially in the boundaries between the ground and the forested area, CSs were distributed densely. On the other hand, PSs were distributed more in far-range and less in near-range as the range dependency of the dispersion index has been shown because of the incident angle dependency particular for airborne SAR geometry. Surprisingly, the number of scatterers to be CS and PS in common was only 20. Even though both CSs and PSs show the same quality in the sense of the phase stability, their distributions were completely different. It indicates that the CS technique based on the SLC can detect the phase stable scatterers which are not detected by the PS technique based on the dispersion index, and vice versa. If the number of phase stable scatterers for the phase calibration is less in the scene, the employment of both the CS technique and the PS technique complementally might be useful to increase the number of phase stable scatterers.

In Chapter 5, as an application of CSs, a methodology to estimate the phase error in repeat-pass interferograms over forest environment by means of CSs were addressed and its performance was demonstrated by employing multibaseline P- and L-band data acquired in the frame of BIOSAR2008 campaign. The number of the available SAR images for P-and L-band analysis over the same scene were 6, respectively. The phase errors in repeat-pass interferograms were modeled to be induced by the baseline error. It has been shown that the impact of the baseline error is severe for the shorter spatial baseline length, and the shorter wavelength data. Regarding with the L-band interferograms acquired with the shorter baseline, there are demands to employ them since they may show the interferometric coherence in an available level even over the distributed target area.

If we consider a simple geometric argument, the double-bounce scattering due to the interactions between the tree-trunk and the ground can be regarded as point-like scattering mechanism located on the ground. This indicates that the phase center of the double-bounce scattering is localized on the ground for interferograms of co-polarization channel, that is, HH or VV. The phase error was estimated by tracking such scatterers whose phase is deterministic and localized on the ground.

In order to detect scatterers which are suitable for the phase calibration, the CS technique was focused. In addition to the azimuth SLC estimated by HH-VV polarization channel images, detection of the phase calibrators with double-bounce scattering mechanism were performed based on the ensemble coherence and the polarimetric alpha angle filter. It has been shown that the number of detected CSs was more in P-band result than in L-band result because of the difference of the scattering mechanism caused by the difference of the wavelength.

After the detection of CSs employed for the phase calibration, the estimations of the baseline error based on a model which employs the phase information of CSs have been performed. Even for the quite low coherence region where is covered with vegetation, the model can estimate the baseline error as far as CSs can be acquired.

In the end, the performance of the phase calibration was validated by employing P- and L-band multibaseline data. In order to validate the accuracy of the phase calibration, CRs, which were allocated in the scene and their position information were measured by GPS, were employed.

For both P- and L-band interferograms, it has been shown that the phase error components were removed well and it resulted in improving the phase stability, especially for L-band data which are sensitive to the phase error. After the phase calibration of each interferograms, P- and L-band DEM were generated by employing multibaseline data. It has been shown that the final error height of CRs become the accuracy within 1m in the case that the number of CSs is enough. In this manner, the potential of CSs as being the phase stable scatterer as PSs has been demonstrated.

The interferograms of HH polarization channel were employed for the phase error estimation. Since the phase error induced by the baseline error is polarization independent, therefore the phase error estimated by employing interferograms of HH polarization can be applied to interferograms with other polarizations for the phase calibration. It is expected that the estimation of the forest physical parameters or the reconstruction of a complex vertical structure of forested area by means of multibaseline polarimetric SAR interferometric data would be accomplished in higher accuracy due the phase calibration by CSs.

As it is still open question for the persistent (or permanent) scatterer interferometry (PSI) community that which natural or artificial targets are associated as phase stable scatterers [108], the identification of CSs is also an issue to be clear. Higher resolution SAR systems such as DLR's F-SAR or TerraSAR-X might disclose these open points. For your reference, TerraSAR-X in high resolution spotlight mode transmits a linear FM signal with 300MHz bandwidth and results in achieving 1m resolution [109]. (New scheme for CS detection from data acquired in spotlight mode is also expected to be developed.)

As another option to identify CS with the scatterer in the imaged scene, the utilization of the broadband ground-based SAR (GB-SAR) system might be also powerful tool. GB-SAR enables the flexible imaging of the scene in the sense that the imaging condition such as the target, the time, and the data acquisition configuration can be changed according to the purposes with high freedom. In order to do so, the difference of the imaging principle, for example the transmitted pulse is not a linear FM pulse but a stepped frequency continuous-wave, should be taken into account for the equivalent analysis.

In this thesis, many of SAR data acquired by airborne SAR systems have been employed with taking the spaceborne SAR application into account. Recalling the recent advances in SAR system development, the development of airborne SAR systems with full polarimetric function has driven up the development of spaceborne SAR systems with full polarimetric function. In fact, the Canadian CCRS has developed C-band RADARSAT-2 based on the experience of Convair-580, German DLR has developed X-band TerraSAR-X based on the experience of E-SAR, and Japanese JAXA has developed L-band PALSAR based on the experience of Pi-SAR. In this manner, it has been shown that the development of airborne SAR systems is fundamental to extend the new applications.

However, looking at the recent situation of Japanese airborne SAR system development, Japanese SAR community seems to have forgotten this fact. The research and development with continuous and systematic efforts are necessary for the creation of the new idea and new direction, I believe. Speaking of the K&C initiative, the initiative itself is quite challenging and may deserve the respect from everyone. However, where is the essential contribution by Japanese SAR community except the data acquisition and provision in the initiative? Furthermore, traditionally the development of L-band SAR system has been preceded mainly in Japan. Needless to say, L-band is not only for Japan [109].

Without the accumulation of technical and scientific investigations, it is difficult to create a new idea and new direction. In order to get them, the improvements of airborne SAR system, moreover GB-SAR system, are strongly required. To leave the positive footprints in this "Golden age of SAR".

Appendix: Quadrature Demodulation Process of SAR Signals

Here, it is shown that the SAR image spectrum is not necessarily symmetry with respect to zero frequency. The pulses transmitted and received by the radar system are real signals. If the signal $g(t)$ is real, then the spectrum $G(f)$ has conjugate symmetry, that is, the real part of $G(f)$ is symmetrical with respect to zero frequency and the imaginary part is antisymmetrical as represented by

$$G(f) = G^*(-f) \tag{A.1}$$

For complex signals, this symmetry does not hold. This means that positive frequencies can be distinguished from negative frequencies, so that positive and negative frequencies can present independent information in complex signals. Please note that if the target is point-scatterer, the SAR spectrum covers wide range of bandwidth and becomes symmetry with respect to zero frequency. The CS technique employs this property for point-like scatterer detection.

In the physical world, all signals are real. However, within the digital signal processor including SAR signal processor, it is convenient, and often more efficient to operate on complex signals. In practice, a real-valued signal is converted to a complex-valued signal that contains the same information, using a complex demodulation process called the quadrature demodulation. The conversion to a complex signal can be performed by employing a Hilbert transformation, which generate a signal whose phase is shifted by $\pi/2$.

At first, this note explains how the received signal can be bandshifted, to obtain a complex baseband signal by a quadrature demodulation process. Then after the SAR spectrum are analyzed by employing processed SAR data to discuss the symmetrical property of SAR spectrum with respect to zero frequency.

A.1 Theory of Quadrature Demodulation

This part is mainly quoted from [110]. Let a general real-valued signal, having a high frequency carrier and a low frequency modulation represented as

$$x(\tau) = \cos\{2\pi f_0 \tau + \phi(\tau)\} \tag{A.2}$$

where the frequency of the carrier, f_0, is several orders of magnitude higher than bandwidth of the modulation, $\phi(\tau)$ (GHz versus MHz).

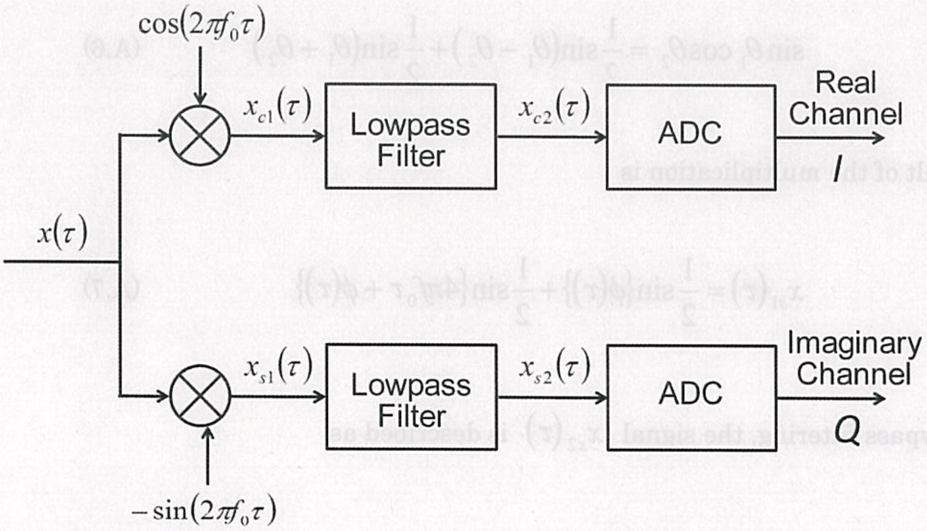


Fig. A.1 Quadrature Demodulation of a Signal to remove the Carrier

Fig. A.1 shows that the quadrature demodulation process produces two channels that represent a complex-valued output. First, we consider the upper channel, where the signal is multiplied by $\cos(2\pi f_0 \tau)$. Employing the trigonometric identity described as

$$\cos\theta_1 \cos\theta_2 = \frac{1}{2}\cos(\theta_1 - \theta_2) + \frac{1}{2}\cos(\theta_1 + \theta_2) \tag{A.3}$$

The result of the multiplication is

$$x_{c1}(\tau) = \frac{1}{2}\cos\{\phi(\tau)\} + \frac{1}{2}\cos\{4\pi f_0 \tau + \phi(\tau)\} \tag{A.4}$$

The first cosine term of (A.4) has an upper frequency governed by the bandwidth of $\phi(\tau)$, while the second cosine term has a much higher frequency, centered around $2f_0$. Therefore, the second term can be removed by a lowpass filter, giving the result

$$x_{c2}(\tau)=\frac{1}{2}\cos\{\phi(\tau)\} \tag{A.5}$$

Similarly, the lower channel of Fig. A.1 is multiplied by $-\sin(2\pi f_0\tau)$, and the following trigonometric identity is employed to express the signal as the sum of high and low frequency components.

$$\sin\theta_1\cos\theta_2=\frac{1}{2}\sin(\theta_1-\theta_2)+\frac{1}{2}\sin(\theta_1+\theta_2) \tag{A.6}$$

The result of the multiplication is

$$x_{s1}(\tau)=\frac{1}{2}\sin\{\phi(\tau)\}+\frac{1}{2}\sin\{4\pi f_0\tau+\phi(\tau)\} \tag{A.7}$$

After lowpass filtering, the signal $x_{s2}(\tau)$ is described as

$$x_{s2}(\tau)=\frac{1}{2}\sin\{\phi(\tau)\} \tag{A.8}$$

The signals $x_{c2}(\tau)$ and $x_{s2}(\tau)$ are then sampled by the analog-to-digital converters (ADCs), at a rate at least equal to the bandwidth of $\phi(\tau)$. Because of the cosine and sine multiplication, the two signals are in phase quadrature, and represent a complex signal as

$$x_3(\tau)=x_{c2}(\tau)+jx_{s2}(\tau)=\frac{1}{2}\exp\{j\phi(\tau)\} \tag{A.9}$$

The two individual signals are called the quadrature components of the complex signal, or the I and Q channels for in-phase and quadrature. The signal $x_3(\tau)$ is the required baseband signal, which is used in the processing of the SAR signals. Fig. 2.1 illustrates the example of complex SAR signal.

In order to show the rationale that (A.1) is true for real signal and not true for complex signal, mathematical expressions are derived here.

For the generality, we assume a complex signal in time domain at first as

$$z(t) = a(t) + jb(t) \tag{A.10}$$

where both $a(t)$ and $b(t)$ are real number and represent the real part and the imaginary part of the complex signal $z(t)$. Performing Fourier transform to (A.10), we get

$$\begin{aligned} Z(f) &= A(f) + jB(f) \\ &= (A_r + jA_i) + j(B_r + jB_i) = (A_r - B_i) + j(A_i + B_r) \end{aligned} \tag{A.11}$$

with

$$A(f) = A_r + jA_i \text{ and } B(f) = B_r + jB_i \tag{A.12}$$

Subscript r and i represent the real and the imaginary part, respectively. Considering the negative frequency of the spectrum $Z(f)$, (A.11) becomes

$$Z(-f) = (A_r - jA_i) + j(B_r - jB_i) = (A_r + B_i) - j(A_i - B_r) \tag{A.13}$$

The magnitude of each spectrum are represented as

$$\begin{aligned} |Z(f)|^2 &= (A_r - B_i)^2 + (A_i + B_r)^2 \\ &= A_r^2 + B_i^2 - 2A_rB_i + A_i^2 + B_r^2 + 2A_iB_r \end{aligned} \tag{A.14}$$

$$|Z(-f)|^2 = A_r^2 + B_i^2 + 2A_rB_i + A_i^2 + B_r^2 - 2A_iB_r \tag{A.15}$$

As can be observed, if $z(t)$ is real signal, that is $b(t)$ is zero, the spectrum has conjugate symmetry, that is the real part of $Z(f)$ is symmetrical about zero frequency and the imaginary part is antisymmetrical as represented in (A.1). For complex signal, this symmetry does not hold, and it means that the positive frequencies can be distinguish from negative frequencies, so that positive and negative frequencies can represent independent information in complex signal.

A.2 Experimental Analysis

In order to discuss the symmetrical property of SAR spectrum with respect to zero frequency, the processed SAR range spectrum is analyzed here. Fig. A.2 shows the employed P-band SAR image with HH polarization. Azimuth increases from bottom to top and range from left to right. Both the processed range bandwidth and the sampling frequency were 100MHz. By performing one-dimensional Fourier transform to the SAR image, the range spectra can be obtained as represented in Fig. A.3.

Fig. A.2 SAR Image

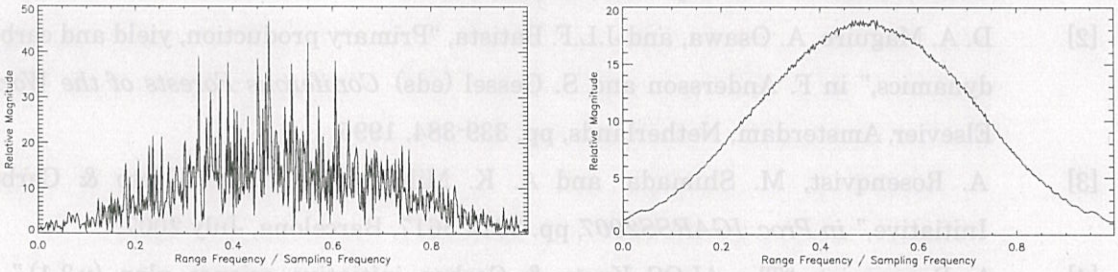
HH Pol. Azimuth increases from bottom to top and range from left to right.

Fig. A.3 Range Spectra of SAR Image

Azimuth increases from bottom to top and range frequency from left to right with centering zero frequency

Fig. A.4 (a) and (b) represent the profile of the magnitude of range spectrum acquired by a single range line and by averaging all the range lines to azimuth direction, respectively. Since the range spectra were weighted by the Hamming window, which shows the symmetric shape, to suppress the sidelobes, it is difficult to discuss the symmetric property based on the magnitude of the spectrum.

Fig. A.5 represents the histogram of phases which were acquired by summing (not subtracting) the phase of the negative frequency part and the positive frequency part. Full range spectrum was split into halves and positive frequency part was reversed so that the symmetrical property can be discussed, then the phases in the negative frequency part and the positive frequency past were summed. If the relationship described in (A.1) holds, that is, the spectrum is symmetrical with respect to zero frequency, the summation should indicates 0 [rad]. However, Fig. A.5 does not reflect the relationship and shows that the phases between the negative part and the positive part are distinguishable. We can see that the SAR image spectrum is not necessarily symmetry with respect to zero frequency since the signal type of SAR signal is complex.



(a) Single Line (b) Averaged to Azimuth Direction

Fig. A.4 Range Spectrum

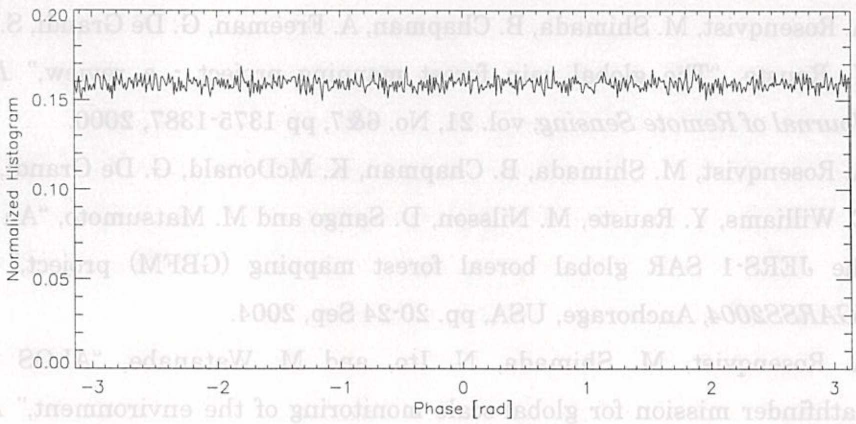


Fig. A.5 Summation of Phases of Negative Frequency Part and Positive Frequency Part

Bibliography

[1] The Botanical Garden of Tohoku University Guidebook, ISBN978-4-86163-120-7 C0045, Tohoku University Press, Sendai, 2009.

[2] D. A. Maguire, A. Osawa, and J.L.F. Batista, "Primary production, yield and carbon dynamics," in F. Andersson and S. Gessel (eds) *Coniferous Forests of the World.* Elsevier, Amsterdam, Netherlands, pp. 339-384, 1995.

[3] A. Rosenqvist, M. Shimada, and A. K. Milne, "The ALOS Kyoto & Carbon Initiative," *in Proc. IGARSS2007,* pp. 3614-3617, Barcelona, July 2007.

[4] A. Rosenqvist, "The ALOS Kyoto & Carbon initiative science plan (v.3.1)," in http://www.eorc.jaxa.jp/ALOS/kyoto/kyoto_jindex.htm, Mar. 2008.

[5] Japan Aerospace Exploration Agency Earth Observation Research Center, "The ALOS Kyoto & Carbon initiative science team reports phase 1 (2006-2008)," JAXA EORC NDX-100003, Jan. 2010.

[6] A. Rosenqvist, M. Shimada, B. Chapman, A. Freeman, G. De Grandi, S. Saatchi and Y. Rauste, "The global rain forest mapping project - a review," *International Journal of Remote Sensing,* vol. 21, No. 6&7, pp 1375-1387, 2000.

[7] A. Rosenqvist, M. Shimada, B. Chapman, K. McDonald, G. De Grandi, H. Jonsson, C. Williams, Y. Rauste, M. Nilsson, D. Sango and M. Matsumoto, "An Overview of the JERS-1 SAR global boreal forest mapping (GBFM) project," *in Proc. of IGARSS2004,* Anchorage, USA, pp. 20-24 Sep, 2004.

[8] A. Rosenqvist, M. Shimada, N. Ito, and M. Watanabe, "ALOS PALSAR: A pathfinder mission for global-scale monitoring of the environment," *IEEE Trans. Geosci. Remote Sens.*, vol. 45, no. 11, pp. 3307–3316, Nov. 2007.

[9] Y. Yamaguchi, W. M. Boerner, J. Yang, R. Sato, and H. Yamada "ALOS-PALSAR quad. pol. images and their applications," *in Proc. of APSAR 2009.* Digital Object Identifier: 10.1109/APSAR.2009.5374213 Publication, pp. 755 - 758, 2009.

[10] S. R. Cloude and K. P. Papathanassiou, "Polarimetric SAR interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 36, no. 5, pp. 1551-1565, Sep. 1998.

[11] K. P. Papathanassiou and S. R. Cloude, "Single-baseline polarimetric SAR

interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 39, no. 11, pp. 2352-2363, Nov. 2001.

[12] W. M. Boerner, "Recent advances in SAR remote sensing: Multimodal POLinSAR imaging with applications to remote sensing of the terrestrial covers and the monitoring of environmental stress changes," *in Proc. of Applied Electromagnetics Conference (AEMC) 2009*, Kolkata, India, pp. 1 – 8, Dec. 2009.

[13] H. Yamada, Y. Yamaguchi, K. Yunjin, E. Rodriguez, and W. M. Boerner, "Polarimetric SAR interferometry for forest analysis based on the ESPRIT algorithm," IEICE Trans Electron. Vol. E84-C, No. 12, pp. 1917-1924, Dec. 2001.

[14] K. Sato, H. Yamada, and Y. Yamaguchi, "Advantage of the ESPRIT method in polarimetric interferometry for forest analysis," IEICE Trans Electron. Vol. E86-B, No. 5, pp. 1666-1672, May 2003.

[15] H. A. Zebker and J. Villasenor, "Decorrelation in interferometric radar echoes," *IEEE Trans. Geosci. Remote Sensing*, vol. 30, no. 5, pp. 950-959, Sep. 1992.

[16] K. P. Papathanassiou and S. R. Cloude, "The effect of temporal decorrelation on the inversion of forest parameters from Pol-InSAR data," *in Proc. of IGARSS 2003*, Toulouse, France, pp. 1429-1431, Jul. 2003.

[17] M. Lavalle, E. Pottier, D. Solimini, Y. L. Desnos, N. Miranda, B. Rosich, and M. Santuari, "A new approach for PolInSAR forest parameter inversion: Results using the ESA ALOS-PALSAR prototype processor,"

[18] Y. S. Zhou, W. Hong, F. Cao, Y. P. Wang, and Y. R. Wu, "Analysis of temporal decorrelation in dual-baseline polinsar vegetation parameter estimation," *in Proc. of IGARSS 2008*, Boston, USA. pp. 473-476, Jul. 2008.

[19] Y. S. Zhou, W. Hong, and F. Cao, "Investigation on the applications of decorrelation analysis in polarimetric SAR interferometry," *in Proc. of IGARSS 2009*, Cape Town, South Africa. pp. 2-254-257, Jul. 2009.

[20] G. Krieger, A. Moreira, H. Fiedler, I. Hajnsek M. Werner, M. Younis, and M. Zink, "TanDEM-X: A satellite formation for high-resolution SAR interferometry," *IEEE Trans. Geosci. Remote Sensing*, vol. 45, no. 11, pp. 3317-3341, Nov. 2007.

[21] S. Tebaldini, and A. M. Guarnieri, "On the role of phase stability in SAR multibaseline applications," *IEEE Trans. Geosci. Remote Sens.*, to be published.

[22] A. Ferretti, C. Prati and F. Rocca, "Permanent scatterers in SAR interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 39, no. 1, pp. 8-20, Jan. 2001.

[23] A. Ferretti, F. Novali, F. D. Zan and F. Rocca, "Moving from PS to slowly decorrelating targets: A prospective view," *in Proc. EUSAR*, 2008, vol. 4, pp. 223-226.

[24] R. Z. Schneider, K. P. Papathanassiou, I. Hajnsek and A. Moreira, "Polarimetric and interferometric characterization of coherent scatterers in urban areas," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 4, pp. 971-984, Apr. 2006.

[25] J. C. Souyris, C. Henry, and F. Adragna, "On the use of complex SAR image spectral analysis for target detection: Assessment of polarimetry," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 12, pp. 2725-2734, Dec. 2003.

[26] K. Ouchi and H. Wang, "Interlook cross-correlation function of speckle in SAR images of sea surface processed with partially overlapped subapertures," *IEEE Trans. Geosci. Remote Sens.*, vol. 43, no. 4, pp. 695-701, Apr. 2005.

[27] K. Ouchi, S. Tamaki, H. Yagushi, and M. Iehara, "Ship detection based on coherence images derived from cross correlation of multilook SAR images," *IEEE Trans. Geosci. Remote Sens. Lett.*, vol. 1, no. 3, pp. 184-187, 2004.

[28] L. Ferro-Famil, A. Reigber, E. Pottier and W.-M Boerner, "Scene characterization using subaperture polarimetric SAR data," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 10, pp. 2264-2276, Oct. 2003.

[29] L. Ferro-Famil, A. Reigber and E. Pottier, "Non-stationary natural media analysis from polarimetric SAR data using a 2-D time-frequency decomposition approach," *Canadian Journal of Remote Sensing.*, vol. 31, no. 1, pp. 21-29, Feb. 2005.

[30] K. Ouchi, "Principles of synthetic aperture radar for remote sensing," Tokyo Denki Daigaku Publication, Tokyo, 2004, ISBN4-501-32330-2.

[31] C. Oliver and S. Quegan, "Understanding synthetic aperture radar images," SciTech Publishing, 2004, ISBN1-891121-31-6

[32] Z. S. Zhou, W. M. Boerner, M. Sato, "Development of a ground based polarimetric broadband SAR system for noninvasive ground-truth validation in vegetation monitoring," *IEEE Trans. Geosci. Remote Sensing*, vol. 42, no. 9, pp. 1803-1810, Sep. 2004.

[33] Y. Yamaguchi, "Radar polarimetry from basics to applications: Radar remote sensing using polarimetric information," IEIC, Tokyo, ISBN 978-4-88552-227-7, pp. 11-44.

[34] J. S. Lee and E. Pottier, "polarimetric radar imaging: from basics to applications," CRC press, ISBN 978-1-4200-5497-2, pp.31-51.

[35] W. M. Boerner, H. Mott, E. Lüneburg, C. Livingston, B. Brisco, R. J. Brown and J. S. Paterson with contributions by S.R. Cloude, E. Krogager, J. S. Lee, D. L. Schuler, J. J. van Zyl, D. Randall, P. Budkewitsch and E. Pottier, 1998, "*Polarimetry in Radar Remote Sensing: Basic and Applied Concepts,*" Chapter 5 in F.M. Henderson, and A.J. Lewis, (eds.), *Principles and Applications of Imaging Radar*, vol. 2 of *Manual of*

Remote Sensing, (ed. R.A. Reyerson), Third Edition, John Willey & Sons, New York, 940 p, ISBN: 0-471-29406-3. pp. 271-358.

[36] W. L. Cameron, N. N. Youssef, L. K. Leung, "Simulated polarimetric signatures of primitive geometrical shapes," *IEEE Trans. Geosci. Remote Sensing*, vol. 34, no. 3, pp. 793-803, May 1996.

[37] R. Touzi, F. Charbonneau, "Characterization of target symmetric scattering using polarimetric SARs," *IEEE Trans. Geosci. Remote Sensing*, vol. 40, no. 11, pp. 2507-2516, Nov. 2002.

[38] S. R. Cloude and E. Pottier, "A Review of Target Decomposition Theorems in Radar Polarimetry," *IEEE Trans. Geosci. Remote Sensing*, vol. 34, no. 2, pp. 498-518, Mar. 1996.

[39] S. R. Cloude, and E. Pottier, "An Entropy Based Classification Scheme for Land Applications of Polarimetric SAR," *IEEE Trans. Geosci. Remote Sensing*, vol. 35, no. 1, pp. 68-78, Jan. 1997.

[40] A. Freeman and S. L. Durden, "A Three-Component Scattering Model for Polarimetric SAR Data", *IEEE Trans. Geosci. Remote Sensing*, vol. 36, no. 3, May 1998.

[41] J. S. Lee, M. R. Grunes, T. L. Ainsworth, L. J. Du, D. L. Schuler, and S. R. Cloude, "Unsupervised Classification using Polarimetric Decomposition and the Complex Wishart Distribution," *IEEE Trans. Geosci. Remote Sensing*, vol. 37, no. 5/1, p 2249-2259, Sep. 1999.

[42] T. Moriyama, M, Nakamura, Y. Yamaguchi, H. Yamada, W. -M. Boerner, "Classification of target buried in the underground by radar polarimetry," *J-IEICE Trans. Commun.*, vol.E82-B, no.6, pp.951-957, Jun. 1999.

[43] R. N. Treuhaft, and S. R. Cloude, "The Structure of Oriented Vegetation from Polarimetric Entropy," *IEEE Trans. Geosci. Remote Sensing*, vol. 37, no. 5/2, pp. 2620-2624, Sep. 1999.

[44] H. Zebker and R. Goldstein, "Topographic mapping from interferometric SAR observation," *J. Geophys. Res.*, vol. 91, no. B5, pp. 4993-5001, 1986.

[45] D. Massonnet and T. Rabaute, "Radar Interferometry: Limits and potential," *IEEE Trans. Geosci. Remote Sensing*, vol. 31, no. 2, pp. 455-464, 1993.

[46] R. Bamler and P. Hartl, "Synthetic aperture radar interferometry," *Inverse Problems*, vol. 14, pp. R1-R54, 1998.

[47] D. Massonnet and T. Rabaute, "Radar Interferometry: Limits and potential," *IEEE Trans. Geosci. Remote Sensing*, vol. 31, no. 2, pp. 455-464, 1993.

[48] F. K. Li and R. M. Goldstein, "Studies of multibaseline spaceborne interferometric

synthetic aperture radar," *IEEE Trans. Geosci. Remote Sens.*, vol. 28, no. 1, pp. 88-96, Jan. 1990.

[49] S. N. Madsen, H. A. Zebker and J. M. Martin, "Topographic mapping using radar interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 31, no. 1, pp. 246-256, Jan. 1993.

[50] D. Massonnet and J. C. Souyris, "Imaging with synthetic aperture radar," CRC press, ISBN 978-0-8493-8239-0, 2008.

[51] G. Fornaro and G. Franceschetti, "Imaging registration in interferometric SAR processing," *IEE Proceedings – Radar, Sonar Navi.*, vol. 142, no. 6, pp. 313-320, 1995.

[52] R. Scheiber and A. Moreira, "Coregistration of interfetometric SAR images using spectral diversity," *IEEE Trans. Geosci. Remote Sens.*, vol. 38, no. 5, pp. 2179-2191, Sep. 2000.

[53] M. D. Pritt and J. S. Shipman, "Least-squares two-dimensional phase unwrapping using FFT's," *IEEE Trans. Geosci. Remote Sens.*, vol. 32, no. 3, pp. 706-708, May. 1994.

[54] G. Fornaro, G. Franceschetti and R. Lanari, "Interferometric SAR phase unwrapping using Green's formulation," *IEEE Trans. Geosci. Remote Sens.*, vol. 34, no. 3, pp. 720-727, May. 1996.

[55] R. M. Goldstein, H. A. Zebker and C. L. Werner, "Satellite radar interferometry: Two-dimentional phase unwrapping," *Radio Sci.*, vol. 23, no. 4, pp. 713-720, Jul. 1988.

[56] U. Spagnolini, "2-D phase unwrapping and instantaneous frequency estimation," *IEEE Trans. Geosci. Remote Sens.*, vol. 33, no. 3, pp. 579-589, May. 1995.

[57] R. F. Hanssen, Radar interferometry: Data interpretation and error analysis, Kluwer Academics, 2001.

[58] P. A. Rosen, S. Hensley, I. R. Joughin, F. K. Lin, S. N. Madsen, E. Rodriguez and R. M. Goldstein, "Synthetic aperture radar interferometry," *Proc. IEEE*, vol. 88, no. 3, pp. 333-382, Mar. 2000.

[59] R. Touzi and A. Lopes, "Statistics of the Stokes parameters and of the complex coherence parameters in one-look and multilook speckle fields," *IEEE Trans. Geosci. Remote Sens.*, vol. 34, no. 2, pp. 519-531, Mar. 1996.

[60] J. D. Ballester-Berman, J. M. Lopez-Sanchez, and J. Fortuny-Guasch, "Retrieval of Biophysical Parameters of Agricultural Crops Using Polarimetric SAR Interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 43, no. 4, pp. 683-694, Apr. 2005.

[61] S. R. Cloude and K. P. Papathanassiou, "Three-stage inversion process for polarimetric SAR interferometry," *IEE Proc. -Radar Sonar Navig.*, vol. 150, no. 3, pp. 125-134, Jun. 2003.

[62] T. Moriyama, S. Uratsuka, T. Umehara, H. Maeno, M. Satake, A. Nadai and K. Nakamura, "Polarimetric SAR image analysis using model fit for urban structures," IEICE Trans. Commun., vol. E88-B, No. 3, pp.1234-1243, March 2005.

[63] P. Gamba, B. Houshmand, "A comparison of C and X-Band InSAR data for 3D characterization of an urban area", IEEE Aerospace and Electronic Systems Magazine, Vol. 17, n. 6, pp. 9-15, June 2002.

[64] G. Franceschetti, A. Iodice, and D. Riccio, "A canonical problem in electromagnetic backscattering from buildings," IEEE Trans. Geosci. Remote Sensing, vol. 40, No.8, pp.1787-1801, Aug. 2002.

[65] Z.-G. Xia and F. M. Henderson, "Understanding the relationship between radar responses patterns and the bio- and geophysical parameters of urban areas," IEEE Trans. Geosci. Remote Sensing, vol. 35, No.1, pp.93-100, Jan. 1997.

[66] J.S. Lee, D. L. Shuler, and T. L. Ainsworth, "Polarimetric SAR data compensation for terrain azimuth slope variation," IEEE Trans. Geosci. Remote Sensing, vol. 38, pp.2153-2163, Sept. 2000.

[67] J.S. Lee, D. L. Shuler, and T. L. Ainsworth, E. Krogager, D.Kasilingam and W. M. Boerner, "On the estimation of radar polarization orientation shifts induced by terrain slope," IEEE Trans. Geosci. Remote Sensing, vol. 40, pp.30-41, Jan. 2002.

[68] D. L. Schuler, J. S. Lee, T. L. Ainsworth, and M. R. Grunes, "Terrain topography measurement using multipass polarimetric synthetic aperture radar data," Radio Sci., vol. 35, pp. 813-832, May-June 2000.

[69] H. Kimura, "Calibration of polarimetric PALSAR imagery affected by Faraday rotation using polarization orientation," *IEEE Trans. Geosci. Remote Sensing*, vol. 47, no. 12, pp. 3943-3950, Dec. 2009.

[70] H. Kimura, K. P. Papathanassiou and I. Hajnsek, "Polarization orientation effects in urban areas on SAR data," in Proc. IGARSS2005, Seoul, July 2005.

[71] H. Kimura, "Radar polarization orientation shifts in built-up areas," *IEEE Geosci. Remote Sens. Lett.*, vol. 5, no. 2, pp. 217–221, Apr. 2008.

[72] S. Uratsuka, M. Satake, T. Kobayashi, T. Umehara, A. Nadai, H. Maeno H. Masuko, M. Shimada, "High-resolution dual-bands interferometric and polarimetric airborne SAR (Pi-SAR) and its applications," *in Proc. of IGARSS 2002*, Toronto, Canada, pp. 1720 – 1722, vol.3, Jun. 2008.

[73] A. Freeman and S. L. Durden, "A three-component scattering model for

polarimetric SAR data," IEEE Trans. Geosci. Remote Sensing, vol. 36, No.3, pp.963-973, May 1998.

[74] Y. Yamaguchi, Y. Yajima and H. Yamada, "A four-component decomposition of POLSAR images based on the coherency matrix" IEEE Trans. Geosci. Remote Sensing Letters, vol. 3, No.3, pp.292-296, July 2006.

[75] W. C. Anderson, "Consequences of nonorthogonality on the scattering properties of dihedral reflectors," IEEE Trans. Antennas Propagt., vol. AP-35, no. 10, pp. 1154-1159, Oct. 1987.

[76] I. Hajnsek, F. Kugler, S. K. Lee, and K. P. Papathanassiou, "Tropical forest parameter estimation by means of Pol-InSAR: The INDREX-II Campaign," *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 2, pp. 481-493, Feb. 2009.

[77] A. Reigber and A. Moreira, "First demonstration of airborne SAR tomography using multi-baseline L-band data," *IEEE Trans. Geosci. Remote Sens.*, vol. 38, no. 5, pp. 2142-2152, Sep. 2000.

[78] G. Fornaro, F. Serafino and F. Soldovieri, "Three-dimensional focusing with multipass SAR data," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 3, pp. 507-517, Mar. 2003.

[79] S. Tebaldini, "Forest SAR Tomography: A covariance matching approach," *in Proc. RADARCON*, Rome, Italy, 2008, pp. 1-6.

[80] S. Tebaldini, "Single and multipolarimetric SAR tomography of forested areas: A parametric approach," *IEEE Trans. Geosci. Remote Sens.*, vol. 48, no. 5, pp. 2375-2387, May. 2010.

[81] S. R. Cloude, "Polarization coherency tomography," *Radio Sci.*, vol. 41, Aug. 2006.

[82] S. R. Cloude, "Dual-baseline coherence tomography," *IEEE Trans. Geosci. Remote Sens.*, vol. 4, no. 1, pp. 127-131, Jan. 2007.

[83] J. Praks, F. Kugler, K. P. Papathanassiou, I. Hajnsek and M. Hallikainen, "Height estimation of boreal forest: Interferometric model-based inversion at L- and X-band versus HUTSCAT profiling scatterometer," *IEEE Trans. Geosci. Remote Sens.*, let., vol. 4, no. 3, pp. 466-pp. 470, Jul. 2007.

[84] F. Garestier, P. C. Dubois-Fernandez and K. P. Papathanassiou, "Pine forest height inversion using single-pass X-band PolinSAR data," *IEEE Trans. Geosci. Remote Sens.*, vol. 46, no. 1, pp. 59-pp. 68, Jan. 2008.

[85] M. Nannini, R. Scheiber and A. Moreira, "On the minimum number of tracks for SAR tomography," *in Proc. IGARSS*, Boston, MA, 2008, pp. II-441-II-444.

[86] M. Nannini, R. Scheiber and A. Moreira, "Estimation of the minimum number of tracks for SAR tomography," *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 2, pp.

531-543, Feb. 2009.

[87] D. R. Sheen and L. P. Johnston, "Statistical and spatial properties of forest clutter measured with polarimetric synthetic aperture radar (SAR)," *IEEE Trans. Geosci. Remote Sens.*, vol. 30, no. 3, pp. 578-588, May. 1992.

[88] D. Blacknell and C. J. Oliver, Comments on "Statistical and spatial properties of forest clutter measured with polarimetric synthetic aperture radar," *IEEE Trans. Geosci. Remote Sens.*, vol. 31, no. 5, pp. 1093-1094, Sep. 1993.

[89] K. Iribe and M. Sato, "Analysis of polarization orientation angle shifts by artificial structures," *IEEE Trans. Geosci. Remote Sens.*, vol. 45, no. 11, pp. 3417-3425, Nov. 2007.

[90] Y.-C. Lin and K. Sarabandi, "Electromagnetic scattering model for a tree trunk above a tilted ground plane," *IEEE Trans. Geosci. Remote Sens.*, vol. 33, no. 4, pp. 1063-1070, Jul. 1995.

[91] L. Thirion, E. Colin and C. Dahon, "Capabilities of a forest coherent scattering model applied to radiometry, interferometry, and polarimetry at P- and L-band," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 4, pp. 849-862, Apr. 2006.

[92] H. A. Zebker and J. Villasenor, "Decorrelation in interferometric radar echoes," *IEEE Trans. Geosci. Remote Sens.*, vol. 30, no. 9, pp. 950-959, Jan. 1992.

[93] N. Adam, B. Kampes and M. Eineder, "Development of a scientific permanent scatterer system: Modifications for mixed ERS/ENVISAT time series," *in Proc. ERS & ENVISAT Symposium,* Salzburg , Austria, 2004.

[94] M. I. Skolnik, *Introduction to Radar Systems.* McGraw-Hill, 1962.

[95] H. R. Raemer, *Radar Systems Principles.* CRC Press, 1996.

[96] J. S. Goodman, *Statical Optics.* John Wiley & Sons, Inc., 1985.

[97] S. Tebaldini, "Single and multipolarimetric SAR tomography of forested areas: A parametric approach," *IEEE Trans. Geosci. Remote Sens.*, vol. 48, no. 5, pp. 2375-2387, May. 2010.

[98] P. Prats, A. Reigber, J. J. Mallorqui, R. Scheiber, and A. Moreira, "Estimation of the temporal evolution of the deformation using airborne differential SAR interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 46, no. 4, pp. 1065-1078, Apr. 2008.

[99] A. Reigber, "Correction of residual motion errors in airborne SAR interferometry," *Elec. Lett.*, vol. 37, no. 17, pp 1083-1084, Aug. 2001.

[100] A. Reigber, P. Prats, and J. J. Mallorqui, "Refined estimation of time-varying baseline errors in airborne SAR interferometry," *IEEE Trans. Geosci. Remote Sens. Lett.*, vol. 3, no. 1, pp. 145-149, Jan. 2006.

[101] K. A. C. de Macedo, R. Scheiber, and A. Moreira, "An autofocus approach for residual motion errors with application to airborne repeat-pass SAR interferometry" *IEEE Trans. Geosci. Remote Sens.*, vol. 46, no. 10, pp. 3151-3162, Oct. 2008.

[102] W. Ye, T. S. Yeo, and Z. Bao, "Weighted least-squares estimation of phase error for SAR/ISAR autofocus," *IEEE Trans. Geosci. Remote Sens.*, vol. 37, no. 5, pp. 2487-2494, Sep. 1999.

[103] D. E. Wahl, C. V. Jakowatz, Jr., P. A. Thompson, and D. C. Ghiglia, "New approach to strip-map SAR autofocus," *in Proc. 6th IEEE Digital Signal Process. Workshop*, Yosemite National Park, CA, Oct. 1994, pp. 55-56.

[104] R. F. Hanssen, Radar interferometry: Data interpretation and error analysis, Kluwer Academics, 2001.

[105] A. Danklmayer, and K. A. C. de Macedo, "An experiment on atmospheric effects in airborne interferometryic SAR data," in *Proc. International Symposium on Antenna and Propagation, Niigata, Japan, 2007.*

[106] German Aerospace Center Microwave and Radar Institute and Swedish Defence Research Agency, "Technical assistance for the development of airborne SAR and geophysical measurements during the BIOSAR 2008 experiment," Data Acquisition and Processing Report version 1.2, June, 2009.

[107] K. Iribe, K. P. Papathanassiou, I. Hajnsek, and M. Sato, "Coherent scatterer in forest environment: Detection, properties and its applications," *in Proc. IGARSS 2010*, Hawaii, USA, 2010.

[108] M, Eineder, N. Adam, R. Bamler, N. Yague-Martinez, and H. Breit, "Spaceborne spotlight SAR Interferometry with TerraSAR-X," *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 5, pp. 1524-1535, May. 2009.

[109] G. Krieger, I. Hajnsek, K. Papathanassiou, M. Eineder, M. Younis, F. De Zan, P. Prats, S. Huber, M. Werner, H. Fiedler, A. Freeman, P. Rosen, S. Hensley, W. Johnson, L. Veilleux, B. Grafmueller, R. Werninghaus, R. Bamler, A. Moreira, "The tandem-L mission proposal: Monitoring earth's dynamics with high resolution SAR interferometry," *in Proc. of Radar Con. 2009*, Pasadena, CA, pp. 1-6, May. 2009.

[110] I. G. Cumming and F. H. Wong, *Digital Processing of Synthetic Aperture Radar Data*, ISBN 978-1-58053-058-3 Artech House, MA, 2005

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Publications by the Author

Conference Paper

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Koichi Iribe, Tadashi Hamasaki, Syunichi Kusano, and Motoyuki Sato, 'Quantitative Analysis of Pol-SAR for Target Feature extraction', EUSAR2006, Dresden, Germany, May, 2006

Koichi Iribe and Motoyuki Sato, 'Polarization Orientation Angle Analysis of Pol-SAR Using Multiple Flight Paths Dataset', PIERS2006, Tokyo, Japan, August, 2006

Koichi Iribe and Motoyuki Sato, 'Comparison of L- and X-band POLSAR Data for Characterization of Polarization Orientation Angle Shift Induced by Man-made Structure`, PolInSAR2007, Esrin, Italy, January, 2007

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Journals

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